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X-ray continuum emission spectroscopy from hot dense matter at Gbar pressures[a)]

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We have measured the time-resolved x-ray continuum emission spectrum of ∼30 times compressed polystyrene created at stagnation of spherically convergent shock waves within the Gbar fundamental science campaign at the National Ignition Facility (NIF). From a clean exponential emission slope between 7.7 keV and 8.1 keV photon energy and using an emission model which accounts for reabsorption, we infer the electron temperature of 375±21 eV, which is in good agreement with HYDRA-1D simulations.

I. INTRODUCTION

Precise experimental constraints on the parameter space of hot dense implosion plasmas are a challenging task in order to benchmark models of these extreme states of matter . Especially temperature diagnostics are important to complete or over-constrain measurements of density and pressure to a complete equation of state (EOS) data set.

The implosion of massive spheres is an outstanding tool to characterize the shock Hugoniot of materials approaching pressures of 1 Gbar and temperatures of several hundred eV[1]. For a complete characterization of these dense matter states, at least some constraint on temperature is urgently needed in addition to the classical Hugoniot oberservables density and pressure. As the interesting hot dense matter states around convergence of the spherical compression waves are surrounded by large amounts of still inward moving outer material, which is less dense and less hot, it is difficult to extract the temperature of the core[2]. In indirect drive experiments the experimental geometry is additionally complicated due to the confining high-Z hohlraum which reduces possible lines-of-sight and creates additional background radiation.

Here we report on the application of x-ray continuum emission spectroscopy to determine the core temperature using a gated high efficiency crystal spectrometer which was originally designed for x-ray Thomson scattering[3,4]. While the total x-ray Thomson scattering amplitude is mainly proportional to the number of scattering electrons, and thus nearly exclusively sensitive to the large region of relatively cold plasma surrounding the hot core due to the volumetric weight[2], the strong energy dependence of high energy bremsstrahlung emisson provides a measurement which is very sensitive to the dense and hot core. The key of the measurement presented here is that the continuum emission is recorded at photon energies which are ∼20x above the plasma temperature allowing the relevant radiation to escape the massive CH sphere as well as obtaining high sensitivity to temperature.

II. EXPERIMENT

The experiments were performed within the Gbar EOS campaign of the fundamental science campaign program at the National Ignition Facility (NIF)[1]. The target design is based on the one-dimensional convergent ablator platform, which was developed for the National Ignition Campaign (NIC)[5]. For temperature measurements, a mono-angle crystal spectrometer (MACS), which uses a gated x-ray detector allowing for snapshots with <100 ps time resolution, is added to this platform. Besides recording x-ray scattering signals, this high-efficiency spectrometer is capable of monitoring the bremsstrahlung emission of the dense plasma core around shock convergence in parallel.

In the presented experiment, a massive plastic (CH) sphere was compressed by indirect drive in a near vacuum gas-fill gold hohlraum heated by 176 laser beams with total energy of 1.1 MJ. A detailed sketch of the experimental setup is shown in Fig. 1. The timing of the gated detector was set to be at 480 ps after shock convergence when the reflected shock has created a relatively large region of hot dense matter. Fig. 2 shows simulations of temperature and density at this time using the hydrodynamics code HYDRA-1D. The three regions of dense hot core plasma, surrounding inward moving plasma and ablation zone are marked.

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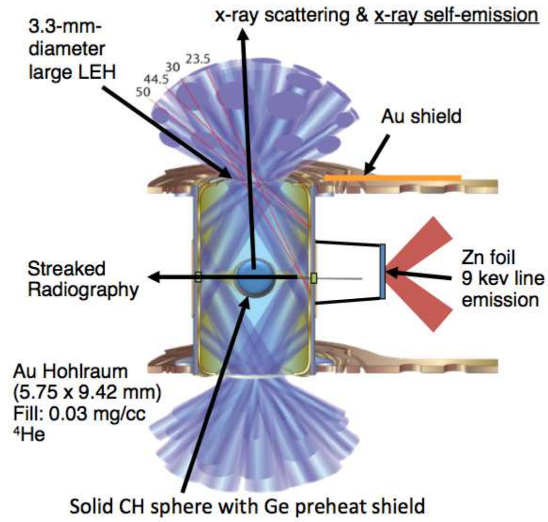

FIG. 1. Experimental setup of the Gbar EOS fundamental science experiments.

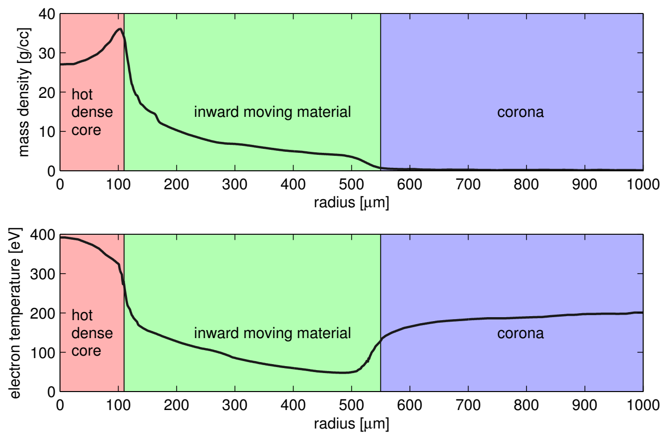

FIG. 2. Hydrodynamic simulations of radial temperature and density profiles at 480 ps after shock convergence.

III. ANALYSIS

For data analysis it needs to be considered that the hot dense matter core is neither optically thin nor optically thick for 7-8 keV x-rays. For an optically thin case, the high energy slope of the emission spectrum is described by free-free bremsstrahlung emission:

$$P_{\rm ff} \propto \frac{Z^2 n_e n_i}{\sqrt{T_e}} \bar{g}_{\rm ff}(h\nu) \exp\left(-\frac{h\nu}{k_B T_e}\right). \quad (1)$$

Here, T_e is the electron temperature, n_e the free electron density, n_i the ion density and Z the ionization state of the plasma. The Gaunt factor $\bar{g}_{\rm ff}(h\nu)$, which is a slowly varying function of photon energy $h\nu$, is assumed to be constant in the relatively narrow spectral window that is investigated by the experiments.

On the other hand, an optically thick plasma in thermal equilibrium follows Planck's law for the spectral emission of radiation, which is only dependent on the equilibrium temperature T:

$$P_{\rm Planck} \propto \frac{\nu^3}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}. \quad (2)$$

The opacity tables, which are used in the HYDRA-1D simulations, calculate the transmission of the whole dense core for 8 keV radiation to ∼50 %. Thus, it is fair to assume free-free bremsstrahlung emission and include opacity effects on the spectral slope by doing ray-tracing of emitted photons through the sample towards the spectrometer. In order to model this radiation transport correctly, the opacity of the surrounding inward moving plasma has to be taken into account as well. For our analysis, we consider an emitting hot dense plasma core of 100 µm radius at constant temperature. We define the spectral opacity weight $W_{h\nu}$ of a sample point at position (x_0, y_0, z_0) contributing to the total emission spectrum as

$$W_{h\nu}(x_0, y_0, z_0) = \exp\left[-\int_{x_0}^{R_S} \rho(x, y_0, z_0)\kappa_{h\nu}(x, y_0, z_0)dx\right], \quad (3)$$

where R_s is the distance of the spectrometer from the center of the imploded sphere, $\rho(x, y_0, z_0)$ is the density at position (x, y_0, z_0) and $\kappa_{h\nu}(x, y_0, z_0)$ is the spectral opacity at position (x, y_0, z_0). Both $\rho(x, y_0, z_0)$ and $\kappa_{h\nu}(x, y_0, z_0)$ are taken from HYDRA-1D, however, both quantities can principally be extracted with high accuracy from the radiography measurements in the same experiment. Performing the spectral opacity weight shows that especially the relatively large bulk of the outer material has a strong influence on the spectral bremsstrahlung shape which is seen by the spectrometer: The low energy end of the interesting spectrum at 7.7 keV experiences a 1.17x stronger attenuation than the high energy end at 8.1 keV. Thus, using the free-free bremsstrahlung model without accounting for opacity, one determines a temperature which is too high since opacity slightly flattens the slope of the emission spectrum.

Evaluating the HYDRA-1D simulations shows that by far the most of the emitted bremsstrahlung radiation power origins from radii between 30 µm and 80 µm for this timing (see Fig. 3). The temperature in this region is predicted to be ∼373 eV. Due to the fact that $P_{\rm ff}$ is proportional to $Z^2 n_e n_i$ and $\exp(-\frac{h\nu}{k_B T_e})$, the contribution of regions of lower temperature and density is insignificant, even after incorporating the relatively large volume of the plasma which surrounds the hot dense core.

In order to extract the spectral bremsstrahlung emission from the detector image, several steps have to be performed: First, a constant non-spectral background needs to be subtracted before the spectral corrections, which include dispersion corrections, filter corrections and spectrally varying solid angles collected by the spectrometer, can be applied. Therefore, the subtraction of

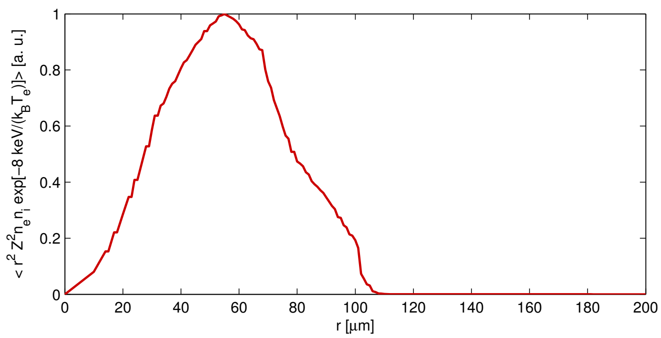

FIG. 3. Average relative contribution to the total recorded bremsstrahlung emission at 8 keV as a function of radius.

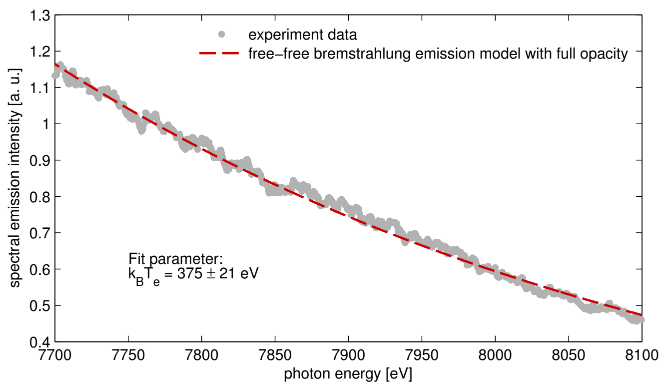

FIG. 4. Measured self emission spectrum compared to free-free bremsstrahlung emission model including opacity effects.

the constant background has direct influence on the resulting spectral slope, which can then be compared with theoretical models. Fig. 4 shows the fit of a free-free bremsstrahlung emission slope accounting for opacity to the recorded spectrum. The resulting electron temperature is 375±21 eV, where the error is dominated by the constant background subtraction. Within the errorbars, this is an excellent agreement with the predictions from the HYDRA-1D simulations. Table I additionally lists results for bremsstrahlung fits without taking opacity into account as well as neglecting the opacity of the bulk material which surrounds the hot core. As expected, this leads to higher temperatures, which are inferred from the spectral slope. Moreover, a Planckian without accounting for opacity was fitted for comparison. Obviously, the resulting temperature is lower compared to the bremsstrahlung model without opacity and actually matches the bremsstrahlung model with full opacity. However this agreement can be classified as random since the plasma is not optically thick enough to emit a Planckian radiation spectrum. Assuming a Planckian core and taking the opacity of the surrounding plasma into account gives a temperature which is below what is predicted by the hydrodynamics simulations.

TABLE I. Fit result for different emission models.

Model	fit parameter k_BT_e [eV]
predictions HYDRA-1D	~373
bremsstrahlung without opacity	445±27
blackbody without opacity	380±21
bremsstrahlung and inner opacity	422±25
blackbody and outer opacity	328±18
bremsstrahlung full opacity	375±21

IV. CONCLUSIONS

The emission spectroscopy provides a very clean measurement of electron temperature in a small region of a hot dense implosion plasma. Applying a free-free bremsstrahlung model taking re-absorption in the emitting hot dense plasma as well as attenuation in the surrounding less hot and less dense material into account, we get a very good agreement with hydrodynamic simulations using HYDRA-1D. The signal-to-noise ratio is excellent, which results in a statistical fitting error in the order of 1 % (2σ). The total error of ~6 % is dominated by the systematic uncertainty of the subtraction of the constant background on the detector. With a better characterization of this background, the precision could even be improved. It has to be said that the current analysis is based on the assumption that the applied density and opacity profiles given by HYDRA-1D are correct. However, the Gbar fundamental science experiments measure density and opacity with high precision radiography in the same experiment. Moreover, x-ray Thomson scattering is principally able to obtain temperature and ionization state of the bulk material at large radii. Thus, combining all these measurements will give the possibility of very powerful equation of state measurements and benchmarks for hot dense plasma models.

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